Index

A

Aluminum, 60, 61, 75

В

bandgap, 49, 50, 52, 54, 55 brittle, 19, 24, 30, 31, 32, 48, 52, 58, 151, 238, 239 Bulk Micromachining, 78

 \mathbf{C}

cantilever, 34, 39, 85, 97, 100, 101, 105, 119, 134, 148, 149, 171, 172, 174, 176, 178, 208, 8

capacitors, 93, 129, 130, 131, 132, 238

Chemical Vapor Deposition, 70

CMOS, 84, 85, 86, 87, 95, 147, 1, 7

Comb Drives, 133

Copper, 62, 63

crystal, 19, 21, 22, 23, 24, 25, 26, 28, 29, 30, 33, 39, 46, 48, 50, 51, 58, 71, 75, 76, 78, 118, 120, 141, 238

crystals, 20, 25, 26, 27, 71

D

device structures, iv

Dislocation

Edge, 28

Screw, 28

Dislocations, 28

dynamics, 168, 214, 215, 216, 220, 243

Ε

ESD, 194, 196, 209, 211

Etching, 73, 75

Dry, 75

Wet, 73

Euler-Bernoulli equation, 95

Evaporation. See Thin Film: Evaporation

Failure, 17, 18, 19, 37, 101, 112, 196, 203, 204, 211, 212, 213, 233, 239, 9 failure mechanisms, ii, iv, 15, 17, 19, 37, 46, 157, 171, 204
Finite Element Analysis, 157, 164
Fracture, 19, 30, 47, 54, 57, 4

G

gallium arsenide, 56, 59, 89 Gold, 61, 62, 127

Η

Harmonic Motors, 139 Heat Transfer Analysis, 158 Hinges, 115, 117, 7 Hooke's law, 98

Ι

Interstitial, 27

L

lamb waves, 109 Lift-off, 73 LIGA, 87, 88, 89, 177 linear, 24, 31, 40, 44, 97, 98, 102, 121, 132, 141, 148, 164, 167, 168, 181

M

Magnetic Actuators, 142
Mask Fabrication, 72
Material properties, iv
membrane, 90, 105, 106, 109, 112, 116, 120, 121
MEMS. See microelectromechanical systems
microelectromechanical systems, iv
Micromotors, 138
Modal Analysis, 166

N

natural frequency, 42, 100

Parallel Plate Capacitors, 129, 132 photolithography, 72, 73 Piezoresistivity, 118 piezoresistors, 120, 121 PMMA, 88 Point Defects, 26 Point Replacement, 27 Poisson's ratio, 22, 23, 55, 57, 61, 62, 107, 157 Polyimides, 63, 64 processing techniques, ii, iv, 65, 78, 89

Q

qualification methodologies, iv

R

radiation, 3, 39, 49, 88, 126, 184, 205, 218 Reactive Growth. *See* Thin Film: Reactive Growth Reliability, i, ii, 4, 6, 117, 121, 127, 140, 145, 150, 1, 3, 4, 6, 7 resonant frequency, 32, 37, 42, 43, 44, 99, 100, 110, 174

S

Shape memory alloy, 149

silicon, 22, 25, 31, 40, 41, 46, 48, 49, 50, 51, 52, 54, 55, 56, 58, 59, 63, 65, 68, 69, 70, 75, 76, 77, 78, 79, 80, 85, 89, 118, 119, 120, 122, 141, 160, 162, 163, 8 silicon nitride, 33, 54, 55, 70, 78, 79, 89

sincon marae, 33, 34, 33, 70, 70, 77, 0

Spin Casting, 65

Sputtering. See Thin Film: Sputtering

Static Analysis, 165

strain, 19, 20, 24, 55, 60, 91, 119, 161, 162, 163, 164, 176, 228

Stress, 19, 24, 60, 112, 160, 161, 164, 169, 175, 177, 4, 5

concentration factor, 24

Structural Beams, 94, 101

Surface Micromachining, 80

T

Test Structures, 171 Thermal Actuators, 147 Thermal Fatigue Stress Analysis, 161 Thin Film, 65 Chemical Vapor Deposition, 70
Evaporation, 66
Growth and Deposition, 65
Reactive Growth, 68
Spin Casting, 65
Sputtering, 66
thin films, 41, 46, 50, 65, 68, 113, 178, 179
Tunneling Tips, 124

V

Vacancies, 26

W

Wafer Bonding, 76
Anodic Bonding, 76
Fusion Bonding, 77
Low-Temperature Glass Bonding, 77

Y

yield strength, 26, 35, 60 Young's modulus, 20, 33, 40, 54, 55, 86, 95, 149, 174, 3, 4

References

- [1] Sammy Kayali, G. Ponchak and R. Shaw, eds., "GaAs MMIC Reliability Assurance Guideline for Space Applications," JPL Publication 96-25, Pasadena, CA, 1996.
- [2] H. C. Nathanson, W. E. Newell, R. A. Wickstrom, and J. R. Davis, Jr., "The Resonant Gate Transistor", *IEEE Transactions on Electron Devices*, March, 1967.
- [3] Helvajian, H. ed. <u>Microengineering Technology for Space Systems</u>, The Aerospace Corporation Report Number ATR-95(8168)-2. El Segundo, CA (September 30, 1995).
- [4] M. R. Douglas and D. M. Kozuch, "DMD Reliability Assessment for Large-Area-Displays," *Society for Information Display International Symposium Digest of Technical Papers*, Vol. 26 (Applications Session A3), pp. 49-52, May 23-25, 1995.
- [5] B. Stark, R. Lawton, D. Vu and S. Kayali, "A Survivability Study on a Microgyroscope Involving Laser Interferometery" JPL D-15753, December 1997.
- [6] Sze, S. M. ed., Semiconductor Sensors, Wiley Inter-Science, New York, 1994.
- [7] B. Eyre and K. Pister, "Micromechanical Resonant Magnetic Sensor in Standard CMOS," 1997 International Conference on Solid State Sensors and Actuators, Chicago, June 16-19, 1997.
- [8] B. Stark and R. Lawton, "Reliability Investigations on a CMOS Magnetometer." JPL D-15768, December 1997.
- [9] Handouts From MSE 331, Professor Grubb, Cornell University, July 6-August 12, 1997.
- [10] Handouts From EE 493: Microelectromechanical Systems, Professor Noel MacDonald, *Cornell University*, January 18- May 2, 1997.
- [11] F. P. Beer and E. R. Johnston, <u>Mechanics of Materials: Second Edition</u>, McGraw-Hill: New York, 1992.
- [12] S. F. Borg and J. J. Gennaro, <u>Advanced Structural Analysis</u>, D. Van Nostrand Company, Inc.: Princeton: 1959.
- [13] C. Barnes, A. Johnston, C. Lee, G. Swift, and B. Rax "Recent Radiation Effects Activities at JPL: Coping with COTS" *Proceedings of the Third ESA Electronic Components Conference*, ESTEC, Noordwijk, The Netherlands, 22-25 April 1997, ESA SP-395.

- [14] D. Maier-Scheider, J. Maibach, and E. Obermeier, "A New Analytical Solution for the Load-Deflection of Square Membranes" *Journal of Microelectromechanical Systems*, Vol. 4, No. 4, December 1995.
- [15] J. W. Judy and R. S. Muller, "Magnetically Actuated Addressable Microstructures", *Journal of Microelectromechanical Systems*, Vol. 6, No. 3, September 1997.
- [16] K. E. Peterson, "Silicon as a Mechanical Material" *Proceedings of the IEEE*, May 1982.
- [17] K. Hjort, J. Söderkvist and J. Schweitz, "Gallium Arsenide as a Mechanical Material" *Journal of Micromechanics and Microengineering* Vol. 4, No. 1, January 1994.
- [18] John T. Milek, <u>Silicon Nitride for Microelectronics Applications</u>, IFI/Plenum, New York, 1971.
- [19] U. Beerschwinger, D. Mathieson, R. L. Reuben, and S. J. Yang, "A study of Wear on MEMS Contact Morphologies" *Journal of Micromechanics and Microengineering* Vol. 7, September 1994.
- [20] W. H. Ko, J. T. Suminto and G. J. Yeh, "Bonding Techniques for Microsensors," *Micromachining and Micropackaging of Transducers*, C. D. Fung, P. W. Cheung, W. H. Ko, and D. G. Fleming, Eds. p. 41.
- [21] K. Fricke, J. Würfl, J. Miao, A. Dehé, D. Rück, and H. L. Hartnagel, "Fabrication of Microstructures for Integrated Sensors on GaAs," *Journal of Micromechanics and Microengineering* Vol. 3, pp. 131-134, 1993.
- [22] L. S. Fan, Y. C. Tai, and R. S. Muller, "IC-Processed Electrostatic Micro-motors." *IEEE International Electronic Devices Meeting*, December 1988.
- [23] Y. C. Tai, L. S. Fan, and R. S. Muller, "IC-Processed Micro-motors: Design, Technology, and Testing" *Proceedings of IEEE Microelectromechanical Systems*, February 1989.
- [24] W. C. Tang, T-C. H. Nguyen, and R. T. Howe. "Laterally Driven Polysilicon Resonant Microstructures." *Proceedings of IEEE Microelectromechanical Systems*, February 1989.
- [25] C. J. Kim, A. P. Pisano, R. S. Muller, and M. G. Lim, "Polysilicon Microgripper". *Technical Digest IEEE Solid-State Sensor and Actuator Workshop*, June 1990.

- [26] F. Ericson, S. Greek, J. Söderkvist and J. Schweitz, "High-sensitivity surface micromachined structures for internal stress and stress gradient evaluation". *Journal of Micromechanics and Microengineering*, Vol. 7, 1997.
- [27] A. T. DiBenedetto, <u>The Structure and Properties of Materials</u>, McGraw-Hill, United States of America, 1967.
- [28] Interview with Jim Okuno on 11-19-97
- [29] C. Barnes, C. Lee, A. Johnston, and R. Lawton, "Radiation Issues for MEMS" *MEMS Reliability and Qualification Workshop*, Pasadena, CA 1997.
- [30] Y. Gianchandani and K. Najafi, "Bent-Beam Strain Sensors" *Journal of Microelectromechanical Systems*, Vol. 5, No. 1, March 1996.
- [31] MIL-STD-45662, *Calibration System Requirements*, Department of Defense, Washington, DC 1988.
- [32] J. G. Collins, W. J. Giardini, A. J. Leistner, and M. J. Kenny "The Influence of Young's Modulus on the Roundness in Silicon Sphere Fabrication" *IEEE Transactions on Instrumentation and Measurement*, Vol. 46, No.2 April 1997.
- [33] Distributor Requirements for Handling Electrostatic Discharge Sensitive (ESDS) Devices, JEDEC Publication EIA 625, EIA & JEDEC Standards & Engineering Publications, 1994.
- [34] MIL-STD-1686, Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices), Department of Defense, Washington, DC, 1992.
- [35] *General Standards For Statistical Process Control*, JEDEC Publication EIA 557A, EIA & JEDEC Standards & Engineering Publications, 1995.
- [36] MIL-I-38535B, *Integrated Circuits (Microcircuits) Manufacturing*, Department of Defense, Washington, DC, June 1, 1993.
- [37] J. Weertman and J. R. Weertman, <u>Elementary Dislocation Theory</u>. Oxford University Press, New York, 1992.
- [38] MIL-STD-8883, *Test Methods and Procedures for Microelectronics*, Department of Defense, Washington, DC, November 15, 1991.

- [39] *Transistor, Gallium Arsenide Power FET, Generic Specification*, JEDEC Publication, JES2, July 1992, EIA & JEDEC Standards & Engineering Publications.
- [40] F. Ericson and J. Å. Schweitz, "Micromechanical Fracture Strength of Silicon" *Journal of Applied Physics*. Vol. 68 pp. 5840-4, 1990.
- [41] T. W. Kenny, W. J. Kaiser, H.K. Rockstad, J. K. Reynolds, J. A. Podosek, and E. C. Vote, "Wide-Bandwidth Electromechanical Actuators for Tunneling Displacement Transducers" *Journal of Microelectromechanical Systems*, Vol. 3, No. 3, September 1994.
- [42] B. Stark, R. Lawton, J. Schiff, T. George, L. Miller, and L. Muller, "Reliability Evaluation of Tunneling Technology for MEMS Devices" JPL D-14729, December 1997.
- [43] P. G. Hartwell, F. M. Bertsch, S. A. Miller, K. L. Turner, and N. C. MacDonald, "Single Mask Lateral Tunneling Accelerometer", *Proceedings of 11th Intl. Workshop on MEMS, Heidelberg, Germany, January 25-29, 1998.*
- [44] J. Koskinun, J. E. Steinwall, R. Soave and H. H. Johnson, "Microtensile Testing of Free-standing Polysilicon Fibers of Various Grain Sizes", *Journal of Micromechanics and Microengineering*, Vol. 3 March 1993.
- [45] W. C. Tang, "Micromechanical Devices: Technology and Reliability Implications" *Microelectronics Reliability and Qualification Workshop*, June 16-17, 1998.
- [46] S. A. Campbell <u>The Science and Engineering of Microelectronic Fabrication</u> Oxford University Press, Oxford, 1996.
- [47] C. J. Wilson and P. A. Beck, "Fracture Testing of Bulk Silicon Microcantilever Beams Subjected to a Side Load" *Journal of Microelectromechanical Systems*, Vol. 5, No. 3, September 1996.
- [48] W. A. Brantley, "Calculated Elastic Constants for Stress Problems Associated with Semiconductor Devices", *Journal of Applied Physics*, Vol. 44, No. 1 January 1973.
- [49] J. J. Wortman and R. A. Evans "Young's Modulus, Shear Modulus, and Poisson's Ratio in Silicon and Germanium", *Journal of Applied Physics*, Vol. 36, No. 1 January 1965.
- [50] D. M. Tanner, N. F. Smith, D. J. Bowman, W. P. Eaton, and K. A Peterson, "First Reliability Test of a Surface Micromachined Microengine Using SHiMMeR" *Proceedings of SPIE*, Vol. 3224, PP 14-23, 1997.

- [51] S. W. Wenzel and R. M. White, "A Multisensor Employing an Ultrasonic Lamb-Wave Oscillator", *IEEE Transactions on Electron Devices*, vol. 35, No.6, June 1988.
- [52] W. Riethmüller and W Benecke, "Thermally Excited Silicon Microactuators" *IEEE Transactions on Electron Devices*, Vol. 35, No. 6, June 1988.
- [53] H. G. Van Bueren, <u>Imperfections In Crystals</u>, North-Holland Publishing Company, Amsterdam, 1960.
- [54] C. M. Harris and C. E. Crede, <u>Shock and Vibration Handbook Volume 1: Basic Theory and Measurements</u>, McGraw-Hill Book Company, Inc., New York, 1961.
- [55] W. Trimmer "Microrobots and Micromechanical systems" *Sensors and Actuators*, Vol.19, No. 3, pp. 267-287, September 1987.
- [56] W. Trimmer <u>Micromechanics and MEMS: Classical and Seminal Papers to 1990</u>, IEEE Press, New York, 1997.
- [57] P. A. Neukomm, H. P. Bornhauser, T. Hochuli, R. Paravicini, and G. Schwarz, "Characteristics of Thin-wire Shape Memory Actuators" *Transducers* '89, *Proceedings of the 5th International Conference on Solid-State Sensors and Actuators*, Vol. 2, pp. 247-252, June 1990.
- [58] S. Timoshenko and Woinowsky-Krieger, <u>Theory of Plates and Shells</u>, 2nd. edition, New York: McGraw-Hill, 1959
- [59] R. Roark, R. and W. Young, <u>Roark's Formulas for Stress and Strain</u>, 6th edition, New York: McGraw-Hill, 1989
- [60] J. Sigley and C. Mischke, <u>Mechanical Engineering Design</u>, 5th edition, New York: McGraw-Hill, 1989.
- [61] R. Blevins, <u>Formulas for Natural Frequency and Mode Shape</u>, New York: Van Nostrand Reinhold, 1979.
- [62] Newell, J., Larson, T. and Cornford S., "A Thermo-mechanical Stress Analysis of an MCM-D Interconnect," Proceedings of the Pan Pacific Microelectronics Symposium, Honolulu, HI, February 1996.
- [63] MIL-STD-1540C, Test Requirements for Launch, Upper-Stage and Space Vehicles, United States Air Force Military Standard, 1994.

- [64] Thomson, W. T., "Theory of Vibration with Applications," 2nd ed., Prentice-Hall, Inc., Engelwood Cliffs, N.J., 1981.
- [65] Meirovitch, L., "Elements of Vibration Analysis," 2nd ed., McGraw-Hill Book Company, New York, 1986.
- [66] Steinberg, D. S., "Vibration Analysis for Electronic Equipment," John Wiley & Sons, Inc., New York, 1986.
- [67] Harris, C. M. (ed.), "Shock and Vibration Handbook," 4th ed., McGraw-Hill Book Company, New York, 1996.
- [68] Marks, L. S. and T. Baumeister, "Mechanical Engineer's Handbook," 6th ed., McGraw-Hill Book Company, New York, 1958.
- [69] Kreith, F. and W. Black, "Basic Heat Transfer," Harper & Row, New York, 1980.
- [70] Kinsler, L. E. and A. R. Frey, "Fundamentals of Acoustics," 2nd ed., John Wiley & Sons, Inc., New York, 1962.
- [71] Himelblau, H., C. Fuller and T. Scharton, "Assessment of Space Vehicle Aeroacoustic Vibration Prediction, Design and Testing," NASA CR-1596, July, 1970.
- [72] NASA-STD-7001, *Payload Vibroacoustic Test Criteria*, National Aeronautics and Space Administration Technical Standard, June 21, 1996.
- [73] Moening, C. J., "Pyrotechnic Shock Flight Failures", *IES Pyrotechnic Shock Tutorial Program*, 31st ATM, Institute of Environmental Sciences, April-May 1985.
- [74] Markstein, H. W., "Designing Electronics for High Vibration and Shock," *Electronic Packaging & Production*, April 1987, pp. 40-43.
- [75] White, D. and M. Mardiguian, "EMI Control Methodology and Procedures," 4th ed., Interference Control Technologies, Gainesville, Virginia, 1986.
- [76] MIL-STD-461, Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference, United States Department of Defense Military Standard, 1986.
- [77] MIL-STD-462, *Electromagnetic Emission and Susceptibility, Test Methods for*, United States Department of Defense Military Standard.
- [78] NASA Preferred Reliability Practice No. PT-TE-1406, "Sinusoidal Vibration."

- [79] NASA Preferred Reliability Practice No. PT-TE-1408A, "Pyrotechnic Shock Testing," May 1996.
- [80] NASA Preferred Reliability Practice No. PT-TE-1412, "Environmental Test Sequencing."
- [81] NASA Preferred Reliability Practice No. PT-TE-1413, "Random Vibration Testing."
- [82] NASA Preferred Reliability Practice No. PT-TE-1431, "Voltage & Temperature Margin Testing," September 1995.
- [83] Wilkerson, T. D., M. Lauriente and G. Sharp, "Space Shuttle Environment," Engineering Foundation, New York, 1985.
- [84] S. L. Miller, G. LaVigne, M. S. Rodgers, J. J. Sniegowski, J. P. Waters, and P. J. McWhorter, "Routes to failure in rotating MEMS devices experiencing sliding friction", *Proceeding of SPIE Micromachined Devices and Components III*, Vol. III, Austin, Sept. 29-30, pp. 24-30.
- [85] Michelle M. Gauthier, <u>Engineering Materials Handbook</u>, ASM desk edition. Materials Park, OH, Nov 1995.
- [86] Handouts provided by G. Fedder, Carnegie-Mellon University.
- [87] S. C. Jacobsen, R. H. Price, J. E. Wood, T. H. Rytting, and M. Rafaelof, "The Wobble Motor: An Electrostatic, Planetary Armature, Microactuator" *Proceedings of IEEE Microelectromechanical Systems*, pp. 17-24, February 1989.
- [88] M. Mehregany, P. Nagarhar, S. Senturia, and J. Lang, "Operation of Microfabricated Harmonic and Ordinary Side-Drive Motors" *Proceedings of IEEE Microelectromechanical Systems*, pp. 1-8, February 1990.
- [89] W. S. Trimmer, K. J. Gabriel, and R. Mahadevan, "Silicon Electrostatic Motors", Transducers '87, The 4th International Conference of Solid-State Sensors and Actuators, pp. 857-860, June 1987.
- [90] W. S. Trimmer and K. J. Gabriel, "Design Considerations for a Practical Electrostatic Micro-Motor", *Sensors and Actuators*, Vol. 11, pp. 189-206, 1987.
- [91] Y. Kanda, "A Graphical Representation of the Piezoresistive Coefficients in Silicon", *IEEE Transactions on Electron Devices*, Vol. ED-29, No. 1, January 1982.
- [92] J. Schiff, B. Eyre, and R. Lawton, "Delamination Effects on Resonant Frequency in a CMOS Magnetometer", *JPL Internal Document*, August 1997.

- [93] K. S. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated Hinges" *Sensors and Actuators A*, Vol. 33, pp. 249-256, 1992.
- [94] L. Y. Lin, S. S. Lee, K. S. Pister, and M. C. Wu, "Micro-Machined Three-Dimensional Micro-Optics for Integrated Free-Space Optical System", *IEEE Photonics Letters*, Vol. 6, No. 12, December 1994.
- [95] M. Tabib-Azar, K. Wong, and W. Ko, "Aging Phenomena in heavily doped (p+) micromachined silicon cantilever beams", *Sensors and Actuators A*, Vol. 33, pp. 199-206, 1992.
- [96] J. B. Angell, S. C. Terry, and P. W. Barth, "Silicon Micromechanical Devices", *Scientific American Journal*, April 1983.
- [97] R. E. Pelrine, "Room Temperature, Open-Loop Levitation of Microdevices Using Diamagnetic Materials", *Proceedings of IEEE Microelectromechanical Systems*, pp. 34-37, February 1990.
- [98] R. E. Pelrine and I. Busch-Vishniac "Magnetically Levitated Micro-Machines", *IEEE Micro Robots and Teleoperators*, November 1987.
- [99] J. W. Judy and R. S. Muller, "Magnetic Microactuation of torsional polysilicon structures," *Sensors and Actuators A, Physical*, vol. A53, nos. 1-3, pp. 392-397, 1996.
- [100] Krane, K, Modern Physics, John Wiley & Sons, New York, 1996.
- [101] Mechanics of Materials 23 1996.
- [102] IEEE Microelectromechanical Systems Workshop, Feb 1993, Florida.
- [103] T. Tsuchiya, O. Tabata, J. Sakata, and Y. Taga, "Specimen Size Effect on Tensile Strength of Surface-Micromachined Polycrystalline Silicon Thin Films" *Journal of Microelectromechanical Systems*, Vol. 7, No.1, March 1998.
- [104] D. G. Oei and S. McCarthy, "The effect of Temperature and Pressure on residual stress in LPCVD polysilicon films," *1992 Materials Research Society Conference*, p. 397.
- [105] M. Sekimoto, H. Yoshihara, and T. Ohkubo, "Silicon Nitride Single-Layer X-Ray Mask." *Journal of Vacuum Science and Technology*, Vol. 21, p 1017, 1982.
- [106] J. W. Judy, D. L. Polla, and W. P. Robbins, "Experimental Model and IC-Process Design of a Nanometer Linear Piezoelectric Stepper Motor" *Microstructures, Sensors* and Actuators, DSC-Vol. 19, pp. 11-17, November 1990.
- [107] K. Ikuta, S. Aritomi, and T. Kabashima, "Tiny Silent Linear Cybernetic Actuator Driven by Piezoelectric Device with Electromagnetic Clamp", *Proceedings IEEE Microelectromechanical Systems*, pp. 232-237, February 1992.

- [108] E. A. Amerasekera and F. N. Najm, <u>Failure Mechanisms in Semiconductor Devices</u>: Second Edition, John Wiley & Sons, New York, 1997.
- [109] S. Kayali "Methodology for MEMS Reliability Evaluation and Qualification" *MEMS Reliability and Qualification Workshop*, Pasadena, CA, August 5, 1997.
- [110] R. Maboudian and R. T. Howe, "Critical Review: Adhesion in Surface Micromechanical Structures" *Journal of Vacuum Science and Technology B*, Vol. 15, January 1997.
- [111] Metals Handbook: 9th Ed. Vol. 2: Properties and Selection of Nonferrous Alloys and Pure Metals, American Society for Metals, 1979.
- [112] D. Bloor, R. J. Brook, M. C. Flemings and S. Mahajan, eds. <u>The Encyclopedia of Advanced Materials</u>, Elsevier Science, Ltd., New York: 1994.
- [113] Presentation by Dr. Virgil Shields, "Silicon Carbide Gas Sensors for Environmental Contaminates." Pasadena, July 9, 1998.
- [114] C. Marxer, M.-A. Grétillat, N. F. de Rooij, R. Bättig, O. Anthamatten, B. Valk and P. Vogel, "Reliability considerations for electrostatic polysilicon actuators using as an example the REMO component" *Sensors and Actuators A*, Vol. 61, pp. 449-454, 1997.
- [115] I. A. Viktorov, <u>Rayleigh and Lamb Waves: Physical Theory and Applications</u>, Plenum Press: New York, 1967.
- [116] J. Zheng, S. Takahashi, S. Yoshikawa, and K. Uchino, "Heat Generation in Multilayer Piezoelectric Actuators" *Journal of the American Ceramics Society*, Vol. 79, No. 12, 1996.
- [117] B. W. Chui, T. D. Stowe, Y. S. Ju, K. E. Goodson, T. W. Kenny, H. J. Mamin, B. D. Terris, R. P. Ried, and D. Rugar, "Low-Stiffness Silicon Cantilevers with Integrated Heaters and Piezoresistive Sensors for High-Density AFM Thermomechanical Data Storage" *Journal of Microelectromechanical Systems*, Vol. 7 No. 1, March 1998.
- [118] D. C. Montgomery and G. C. Runger, <u>Applied Statistics and Probability for Engineers</u>, John Wiley & Sons: New York, 1994.
- [119] L. J. Broutman and R. H. Krock, <u>Modern Composite Materials</u>, Addison Wesley, Reading, Massachusetts: 1967.
- [120] E. Rabinowicz, <u>Friction and Wear of Materials: 2nd Edition</u>, New York, John Wiley & Sons, 1995.
- [121] D. M. Tanner, W. M. Miller, W. P. Eaton, L. W. Irwin, K. A. Peterson, M. T. Dugger, D. C. Senft, N. F. Smith, P. Tangyunyong, and S. L. Miller, "The Effect of Frequency on

- the Lifetime of a Surface Micromachined Microengine Driving a Load" 1998 IEEE International Reliability Physics Symposium Proceedings, March 30-April 2, 1998, pp. 26-35.
- [122] L. D. Edmonds, C. I. Lee, and G. M. Swift, "Radiation Response of MEMS Accelerometer: An Electrostatic Force" 1998 National Space and Radiation Effects Conference, July 20-24, 1998.
- [123] A. R. Knudson, S. Buchner, P. McDonald, W. J. Stapor, A. B. Campbell, K. S. Grabowski, D. L. Knies, S. Lewis, and Y. Zhao, "The Effects of Radiation on MEMS Accelerometers," *IEEE Transactions on Nuclear Science*, vol. 43, pp. 3122-3125, December, 1996.
- [124] J. S. Danel, F. Michel, and G. Delapierre, "Micromachining of Quartz and its application to an Acceleration Sensor" *Sensors and Actuators A*, Vol. A21-A23, pp. 971-977, 1990.
- [125] J. Söderkvist, "Micromachining of Quartz and its application to an Acceleration Sensor" *Sensors and Actuators A*, Vol. A21-A23, pp. 971-977, 1990.
- [126] J.-A. Schweitz "Mechanical characterization of thin films by micromechanical techniques" *MRS Bulletin*, Vol.17, no.7, p. 34-45.
- [127] T. Tsuchiya, O. Tabata, J. Sakata and Y. Taga, "Tensile Testing of Polycrystalline Silicon Thin Films Using Electrostatic Force Grip" *Transactions of the Institute of Electrical Engineers of Japan, Part E*, Vol.116-E, no.10, p. 441-6.
- [128] S. Greek, F. Ericson, S. Johansson and J.-A. Schweitz, "In situ tensile strength measurement of thick-film and thin-film micromachined structures" 8th International Conference on Solid-State Sensors and Actuators and Eurosensors IX, Vol. 2, 1995.
- [129] E. Obermeier, "Mechanical and Thermophysical Properties of Thin Film Materials for MEMS: Techniques and Devices" *Materials Research Society Symposium Proceedings*, Vol. 444.
- [130] D. W. Burns, *Micromechanics of Integrated Sensors and the Planar Processed Pressure Transducer*, Ph.D. Thesis, University of Wisconsin, Madison, 1988.
- [131] E. D. Nicholson and J. E. Field, "The Mechanical and Thermal Properties of Thin Films" *Journal of Hard Materials*, Vol.5, no.3, p. 89-132, 1994.

- [132] J.E. Graebner and S. Jin, "Thermal properties of Optical-Quality Diamond Films" *Proceedings of the SPIE The International Society for Optical Engineering*, Vol.1759, p. 167-77.
- [133] E. Jansen and E. Obermeier "Thermal conductivity measurements on thin films based on micromechanical devices" *Journal of Micromechanics and Microengineering*, Vol. 6, no. 1, p. 118-21, 1996.
- [134] Y. -C. Tai, C. H. Mastrangelo and R. S. Muller, "Thermal Conductivity of Heavily Doped Low-Pressure Chemical Vapor Deposited Polycrystalline Silicon Films" *Journal of Applied Physics*, Vol.63, no. 5, p. 1442-7.
- [135] G. Zhang, *Design and Simulation of A CMOS-MEMS Accelerometer* MS Thesis, Carnegie Mellon University, 1998.
- [136] J. B. Starr, "Squeeze-Film Damping in Solid-State Accelerometers" *Technical Digest IEEE Solid-State Sensor and Actuator Workshop*, June 1990.
- [137] C. S. Pan and W. Hsu, "An Electro-Thermally and Laterally Driven Polysilicon Microactuator" *Journal of Micromechanics and Microengineering*, Vol. 7, p. 7-13, 1997.
- [138] H. Guckel, "Surface Micromachined Pressure Transducers," *Sensors and Actuators A*, Vol. A28, 1991.
- [139] F. J. von Pressig, "Applicability of the Classical Curve-Stress Relation for Thin Films on Plate Substrates" *Journal of Applied Physics*, Vol. 66, p.4262, 1989.
- [140] G. G. Stoney, Proceedings of the Royal Society of London, Vol. A82, p. 172, 1909.
- [141] M. E. Motamedi, M. C. Wu, and K. S. Pister, "Micro-opto-electro-mechanical Devices and On-chip Optical Processing" *Optical Engineering*, Vol. 36, No. 5, May 1997.
- [142] G. K. Fedder, "Integrated MEMS in Conventional CMOS" *Proceedings of the NSF/AFOSR/ASME Workshop on Tribology Issues and Opportunities in MEMS*, Columbus, Ohio, November 1997.
- [143] X. Zhu, "Reliability Implications of Deep-RIE Post CMOS Processing" *MEMS Reliability and Qualification Workshop*, Pasadena, CA, August 1998.
- [144] WWW site: http://mems.mcnc.org/smumps/Mumps.html
- [145] C. M. Jackson, H. J. Wagner, and R. J. Wasilewski, "55-Nitinol, The Alloy with a Memory, its Physical metallurgy, properties, and applications" *NASA-SP-5110*.

- [146] J. Söderkvist, "Similarities Between Piezoelectric, Thermal, and Other Internal Means of Exciting Vibrations" *Journal of Micromechanics and Microengineering*, Vol. 3, pp. 24-31, 1993.
- [147] W. C. Tang, T.-C. H. Nguyen, M. W. Judy and R. T. Howe, "Electrostatic-comb Drive of Lateral Polysilicon Resonators" *Transducers* '89, *Proceedings of the 5th International Conference on Solid-State Sensors and Actuators and Eurosensors III*, Vol. 2, pp. 328-331, June 1990.
- [148] W. C. Tang, M. G. Lim, and R. T. Howe, "Electrostatically balanced Comb Drive for Controlled Levitation" *Technical Digest IEEE Solid-State Sensor and Actuator Workshop*, pp. 23-27, June 1990.
- [149] W. Riethmüller, W. Benecke, U. Schakenburg and A. Heuberger, "Micromechanical Silicon Actuators Based on Thermal Expansion Effects" *Transducers* '87, *The 4th International Conference on Solid-State Sensors and Actuators*, pp. 834-837, June 1987.
- [150] M. Parameswaran, Lj. Ristic, K. Chau, A. M. Robinson, and W. Allegretto, "CMOS Electrothermal Microactuators" *Proceedings IEEE Microelectromechanical Systems*, pp. 128-131, February 1990.
- [151] S. T Cho, K. Najafi, and K. D. Wise, "Scaling and Dielectric Stress Compensation of Ultrasensitive Boron-Doped Silicon Microstructures" *Proceedings IEEE Microelectromechanical Systems*, pp. 50-55, February 1990.
- [152] M. Gordos, "Tribological Behavior of Polycrystalline Diamond and Poly-/Single-Crystal Silicon in Vacuum and Hydrogen for MEMS Micromechanical Applications" *MEMS Reliability and Qualification Workshop*, Pasadena, CA, August 1997.
- [153] B. Bhushan, S. Sundararajan, X. Li, C. A. Zorman, and M. Mehregany, "Micro/Nanotribological Studies of Single-Crystal Silicon and Polysilicon and SiC Films for Use in MEMS Devices" *Proceedings of the NSF/AFOSR/ASME Workshop on Tribology Issues and Opportunities in MEMS*, Columbus, Ohio, November 1997.
- [154] WWW site: http://mems.ee.cornell.edu/macd/
- [155] WWW site: http://synergy.icsl.ucla.edu/
- [156] P. Fortescue and J. P. Stark eds., <u>Spacecraft Systems Engineering</u>, John Wiley & Sons, August 1995.
- [157] WWW site: http://mems.engr.wisc.edu/research.html

- [158] WWW site: http://www.ee.surrey.ac.uk/Personal/D.Banks/umintro.html
- [159] R. M. Moroney, R. M. White, and R. T. Howe, "Ultrasonic Micromotors" *Proceedings IEEE Ultrasonics Symposium*, October 1989.
- [160] V. Milanovic, M. Gaitan, E. D. Bowen, N. H. Tea, and M. E. Zaghloul, "Thermoelectric Power Sensor for Microwave Applications by Commercial CMOS Fabrication" *IEEE Electron Device Letters*, Vol. 18, No. 9, September 1997.
- [161] N. H. Tea, V. Milanovic, C. A. Zincke, J. S. Suehle, M. Gaitan, M. E. Zaghloul, and J. Geist, "Hybrid Postprocessing Etching for CMOS–Compatible MEMS" *Journal of Microelectromechanical Systems*, Vol. 6, No. 4, December 1997.
- [162] J. Maureau, M. C. Sharatchandra, M. Sen, and M. Gad-el-Hak, "Flow and Load Characteristics of Microbearings with Slip" *Journal of Micromechanics and Microengineering*, Vol. 7, pp. 55-64, 1997.
- [163] J. H. Smith, S. Montague, and J. J. Sniegowski, "Material and Processing Issues for the Monolothic Integration of Microelectronics with Surface Micromachined Sensors and Actuators" *Micromachining and Microfabrication* '95, Society for Optical Engineers, October 1995.
- [164] A. Götz, I Gràcia, C. Cané, and E Lora-Tamayo, "Thermal and Mechanical Aspects for Designing Micromachined Low-Power Gas Sensors" *Journal of Micromechanics and Microengineering*, Vol. 7, pp. 247-249, 1997.
- [165] A. de Arragón, "Space Applications of Micro/nano-technologies" *Journal of Micromechanics and Microengineering*, Vol. 8, pp. 54-56, 1998.
- [166] Y. Zhang and K. D. Wise, "Performance of Non-Planar Silicon Diaphragms Under Large Deflections" *Proceedings of Microelectromechanical Systems*, February 1993.
- [167] N. Chong, T. A. S. Srinivas, and H. Ahmed, "Performance of GaAs Microbridge Thermocouple Infrared Detectors" *Journal of Microelectromechanical Systems*, Vol. 6, No. 2, June 1997.
- [168] X. Zhu, D. W. Greve, R. Lawton, N. Presser, and G. K. Fedder, "Factorial Experiment on CMOS-MEMS RIE Post Processing" *Submitted May 1998*.
- [169] C. R. King, L. Y. Lin and M. C. Wu, "Monolithically Integrated Refractive Microlens Standing Perpendicular to the Substrate" *SPIE*, Vol. 2687, pp. 123-130, 1996.

- [170] S. A. Miller, K. L. Turner and N. C. MacDonald, "Microelectromechanical Scanning Probe Instruments for Array Architectures" *Review of Scientific Instruments*, Vol. 68, No. 11, November 1997.
- [171] L. Elbrecht, U. Storm, and J. Binder, "Comparison of Stress Measurement Techniques in Surface Micromachining" *Journal of Micromechanics and Microengineering*, Vol. 7, pp. 151-154, 1997.
- [172] J. S. Suehle, R. E. Cavicchi, M. Gaitan, and S. Semancik, "Tin Oxide Gas Sensor Fabricated Using CMOS Micro-Hotplates and *In-Situ* Processing" *IEEE Electron Device Letters*, Vol. 14, No. 3, March 1993.
- [173] R. E. Cavicchi, J. S. Suehle, K. G. Krieder, M. Gaitan, and P. Chaparala, "Fast Temperature Programmed Sensing for Micro-Hotplate Gas Sensors" *IEEE Electron Device Letter*, Vol. 16, No. 6, June 1995.
- [174] J. R. Choi and D. Polla, "Integration of Microsensors in GaAs MESFET Process" *Journal of Micromechanics and Microengineering*, Vol. 3, pp. 60-64, 1993.
- [175] K.-M. H. Lenssen, H. W. van Kesteren, Th. G. S. M. Rijks, J. C. S. Kools, M. C. de Nooijer, R. Coehoorn and W. Folkerts, "Giant Magnetoresistance and its Application in Recording Heads" *Sensors and Actuators A*, Vol. 60, 1997.
- [176] M. Hisanaga, T. Koumura, and T. Hattori, "Fabrication of 3-Dimensionally Shaped Si Diaphragm Dynamic Focusing Mirror" *Proceedings IEEE. Microelectromechanical Systems*, February 1993.
- [177] M. T. A. Saif and N.C. MacDonald, "Measurements of Forces and Spring Constants of MicroInstuments" *Review of Scientific Instruments*, Vol. 69, No. 3, March 1998.
- [178] L. Rothman, "Properties of Thin Polyimide Films" *Journal of the Electrochemical Society*, pp. 2216-2220, October 1980.
- [179] WWW site: http://www.cnf.cornell.edu
- [180] Shaw, Kevin, and N.C. MacDonald, "SCREAM I: A single mask, single crystal silicon, reactive ion etching process for Microelectromechanical structures." *Sensors and Actuators*, Vol 40, 1994, pp. 63-70.
- [181] P. G. Hartwell, "Deep Silicon RIE with Profile Control" 44th Meeting of the American Vacuum Society, San Jose, Oct 23, 1997.

- [182] T. Tsao, F. Jiang, R. A. Miller, Y. C. Tai, B. Gupta, R. Goodman, S. Tung, and C. M. Ho, "An Integrated MEMS System for Turbulent Boundary Layer Control," *Technical Digest, 1997 International Conference on Solid-State Sensors and Actuators (Transducers* '97), Chicago, IL, Vol. 1, pp. 315-318, Jun. 16-19 1997.
- [183] G. Lin, K.S.J. Pister and K. P. Roos, "Measurement of Contractile Characteristics from Isolated Heart Cells Using a Miniaturized Force Transducer System," *IEEE Engineering in Medicine and Biology Society 16th Annual International Conference*, Baltimore, Maryland, November 3-6, 1994, pp. 1017 1018.
- [184] H. L. Hvims, "Conductive Adhesives for SMT and Potential Applications," IEEE *Trans. on Components, Packaging, and Manuf. Tech. Part-B*, Vol. 18, No. 2, pp. 284-291, May 1995.
- [185] O. Rusanen and J. Lenkkeri, "Reliability Issues of Replacing Solder With Conductive Adhesives in Power Modules," *IEEE Trans. on Components, Packaging, and Manuf. Tech. Part-B*, Vol. 18, No. 2, pp. 320-325, May 1995.
- [186] T. Tuhus and A. Bjomeklett, "Thermal Cycling Reliability of Die Bonding Adhesives," 1993 IEEE Annual Inter. Reliability Physics Symposium Digest, pp. 208, March 23-25, 1993.
- [187] P. Yalamanchili and A. Christou, "Finite Element Analysis of Millimeter Wave MMIC Packages Subjected to Temperature Cycling and Constant Acceleration," 1993 GaAs REL Workshop Programs and Abstracts, October 10, 1993.
- [188] J. Kloeser, E. Zake, F. Bechtold, and H. Reichl, "Reliability Investigations of Fluxless Flip-Chip Interconnections on Green Tape Ceramic Substrates," IEEE *Trans. Components, Packaging, and Manufacturing Technology, Part A*, Vol. 19, No. 1, pp. 24-33, March 1996.
- [189] J. Giesler, G. O'Malley, M. Williams, and S. Machuga, "Flip Chip on Board Connection Technology: Process Characterization and Reliability," *IEEE Trans. Components, Packaging, and Manufacturing Technology, Part 8*, Vol. 17, No. 3, pp. 256-263, August 1994.
- [190] D. Suryanarayana, T. Y. Wu, and J. A. Varcoe, "Encapsulant used in Flip-Chip Packages," *IEEE Trans. Components, Packaging, and Manufacturing Technology*, Vol. 16, No. 8, pp. 858-862, December 1993.

- [191] J. Butler, V. Bright, and J. Comtois, "Advanced multichip module packaging of microelectromechanical systems," *Tech. Digest of the 9th International Conference on Solid-State Sensors and Actuators (Transducers '97)*, Vol. 1, pp. 261-264, June 1997.
- [192] J. Butler, V. Bright, R. Saia and J. Comtois, "Extension of High Density Interconnect Multichip Module Technology for MEMS Packaging," SPIE Vol. 3224, pp. 169 177.
- [193] W. Daum, W. Burdick Jr., and R. Fillion, "Overlay high-density interconnect: A chips-first multichip module technology," *IEEE Computer Society*, vol. 26, no. 4, pp. 23-29, April 1993.
- [194] R. Filtion, R. Wojnarowski, R. Saia, and D. Kuk, "Demonstration of a chip scale chip-on-flex technology" *Proceedings of the 1996 International Conference on Multichip Modules*, SPIE vol. 2794, pp. 351-356, April 1996.
- [195] J. Marshall, M. Parameswaran, M. Zaghloul, and M. Gaitan, "High-level CAD melds micromachined devices with foundries," *Circuits and Devices*, vol. 9, no. 6, pp. 10-17, November 1992.
- [196] T. M. Moore and S. J. Kelsall, "The Impact of Delamination on Stress-Induced and Contamination-Related Failure in Surface Mount ICs," 1992 IEEE Annual Int. Reliability Physics Symposium Proc., pp. 169-176, March 31-April 2, 1992.
- [197] A. A. O. Tay, G. L. Tam, and T. B. Lim, "Predicting Delamination in Plastic IC Packages and Determining Suitable Mold Compound Properties," *IEEE Trans. Components, Packaging, and Manufacturing Technology-Part 8*, Vol. 17, No. 2, pp. 201-208, May 1994.
- [198] W. J. Roesch and A. L. Rubalcava, "GaAs IC Reliability in Plastic Packages," 1995 GaAs Reliability Workshop Programs and Abstracts, pp. 25-30, October 29, 1995.
- [199] A. A. O. Tay, K. S. Yeo, and J. H. Wu, "The Effect of Wirebond Geometry and Die Setting on Wire Sweep," *IEEE Trans. Components, Packaging, and Manufacturing Technology-Part B*, Vol. 18, No. 1, pp. 201-209, February 1995.

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